

Description

Multispectral Imaging System and Methods of Use

5 Cross-Reference to Related Patent Applications

This application is a continuation-in-part of provisional patent application serial no.; 60/454,927 filed 14 March 2003

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Technical Field

The present invention is in the field of electronic imaging. More particularly in the area of multispectral surveillance imaging systems for identifying objects on 15 the surface or under the water.

Background of the Invention

20 The detection and identification of low contrast objects on or below the surface of the ocean has a multitude of commercial applications from detecting dolphin free schools of tuna to counting salmon on the rivers and estuaries of the northwest. Additional uses include the 25 location of debris from maritime and aircraft accidents and the possible location of maritime survivors in a search and rescue operation. Military applications obviously include the detection and location of subsurface threats such as mines, and the avoidance of 30 navigational hazards, such as reefs and shoals. Recent applications in the area of homeland security include the monitoring of harbors, rivers, and lakes for towed contraband and subsurface intrusion by divers.

Optimum processing of ocean imagery for this purpose requires spatial and temporal registration of the image sensor over the entire imaged field of view. Spatial or 5 temporal image mis-registration decorrelates the images and results in a loss of processing gain. Any loss of processing gain results in the reduced ability to detect low contrast targets in the high background imagery of the ocean's surface. Processing gains of at least 33dB 10 are possible for a two-color multispectral image. The processing three or more colors can yield an additional 6dB of gain.

Prior techniques include the use of multiple cameras, 15 single cameras with multiple sensor arrays, and single cameras with a single sensor array. Prior single cameras such as camcorders or digital cameras with single sensor arrays impart both spatial and temporal image mis-registration since the color mosaic (**FIG. 1A**) is affixed 20 to the sensor. A color 'pixel' is comprised of the 4 subpixels **102**, **104**, and **106** shown within the dotted lines. The subpixels do not image the same points on the water; hence give rise to spatial misregistration. A spatial mis-registration of one sub-pixel has been shown 25 to produce a 10dB loss of processing gain. If the sub-pixels are not sampled simultaneously, a temporal mis-registration will result. A difference in the temporal sampling of the pixels imparts a loss of correlation between the channels. For every factor of ten in the 30 temporal difference (10 milliseconds instead of 1 millisecond) the correlation will lose a factor of ten (0.9 instead of 0.99) and the processing gain will lose

20dB, with a resultant reduction in the object detection depth capability.

A single camera with multiple sensors (**FIG.1B**) imparts the mis-registration at the time the sensors are affixed to a beam splitter or prism. As shown in **FIG.1B**, the three light components **120**, **122**, and **124** are spectrally separated into red (**122**), green (**120**), and blue (**124**) through the use of dichroic filters **110** and **112**, and prisms **114**, **116** and **118**. Although dichroic filters can be manufactured with minimal polarization, the multiple reflections in prisms **116** and **118** create a light output that is polarized, primarily in the green and blue channels, while the red channel is relatively unpolarized. This difference can result in a loss of processing gain of up to 9dB if used for the present application.

The use of two cameras requires that both lenses have the same magnification, f-number and focus. Furthermore, some mechanical means of aligning the images to register the same image plane is required in pitch, roll, and yaw. In general, due to coma and other lens effects, this can only be accomplished over 80% of the image for arrays with pixels on the order of 50 or more microns. Alignment to 4 microns is difficult to attain and a re-alignment must be done on a daily basis. Modern sensors have pixels on the order of 9 microns, so it becomes virtually impossible to maintain image registration to less than $\frac{1}{2}$ of a pixel without a subsequent loss of processing gain of 5dB.

Images of the ocean's surface contain several clutter components; light scatter in the atmosphere between the camera and the ocean surface, glint or light reflection from the water surface, hemispherical light scatter from the atmosphere above the ocean, and light from the upwelling irradiance of the water with and without an object.

Consequently there is a need for a multispectral imaging system that has both spatial and temporal registration over the entire imaged field of view as well as being able to reduce or eliminate atmospheric and hemispheric light scatter, light reflection from the waters surface as well as upwelling irradiation from the water.

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Brief Description of the Drawings

FIG.1A is an illustration of a single camera single sensor imager;

20 FIG.1B is an illustration of a single camera multiple sensor imager;

FIG.2 is an illustration of the numerous light components seen by a multispectral imagery sensor during use over water;

25 FIG.3 illustrates the process used to obtain the low contrast multispectral images;

FIG.4 is an illustration of the sensor used in this invention;

30 FIG.5 illustrates the line output of a typical imaging sensor;

FIG.6A is an illustration of typical line outputs for a two-color camera;

FIG. 6B illustrates the line output of a difference channel described in this invention; and

FIG. 7 is a schematic diagram of a camera in one embodiment of the invention.

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Detailed Description of the Invention

The multispectral littoral surveillance system (MLSS) is a system for the detection of low contrast objects on or 10 below the surface of the ocean through the elimination of most of the surface reflected light clutter components from multispectral images. The images are processed by taking the weighted difference of two or more spectral components and preferably applying a demeaning or 15 whitening filter to the result. The images can then be frame averaged where the appropriate corrections for motion, magnification, rotation, and translation have been applied. The resultant imagery can then be displayed to an operator or transmitted to a remote location.

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The multispectral ocean surveillance system uses a camera 218 with a sensor that eliminates the loss of processing gain in the detection of low contrast ocean objects. The new sensor (**FIG. 4**) is an array of three vertically 25 stacked photodiodes (**406**, **408**, and **410**) per pixel that produces a Red, Green and Blue (RGB) output separation due to the spectral absorption of silicon as a function of depth; i.e., the uppermost layer **400** collects photons in the blue spectrum with 'green' and 'red' photons 30 passing into the next layer. This new sensor is now commercially available. (is it commercially available?) The second layer **402** collects photons in the green

spectrum, and the final layer **404** then collects photons in the red part of the spectrum.

The use of the new sensor eliminates the spatial and
5 temporal mis-registration problems inherent in all prior single and multiple device Charge Coupled Device (CCD) and Complimentary Metal Oxide Semiconductor (CMOS) camera designs. The spatial mis-registration is eliminated since the pixels are aligned vertically, and the temporal mis-
10 registration is also eliminated since the multi-color pixels are read out simultaneously in time.

The numerous components of the light collected by the imaging system over the surface of the water **200** are
15 shown in **FIG.2**. The collection platform **202** can be any type of moving aircraft, balloon, UAV, helicopter, space shuttle or satellite, as well as fixed locations such as bridges, ship masts and other sites with a clear view of the water. The collection is normally performed in the
20 daytime, using sunlight as the source of illumination for objects of interest **204**. The sensor **218** is pointed in a direction away from the solar illumination as to eliminate the direct glint reflection component **214** from contributing to the image intensity. United States
25 patent 6,304,664 demonstrates a collection system using a nadir looking sensor with contribution of glint **214**. This would normally result in the saturation of the sensor and the loss of object detection, at least in the area of the ocean image obscured by the glint.

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There are four major components to the light collected by the sensor. The first is the hemispherical light scatter

from the atmosphere 206, which is primarily due to Rayleigh scattering of sunlight 201 and is polarized. The portion of this component seen by the sensor is surface reflection 216. A polarizing filter on the sensor can be

5 used to reduce the surface contribution of this component from the total light collected. Using a polarizing filter with this sensor affects all channels equally to enhance the object detection without a loss of processing gain. The second component is the backscattered portion 220 of
10 the glint 214 reflections. The forward scattering component can be reduced or eliminated by pointing the system in a direction away from the surface reflection of the sun. The third component is the light contribution from atmospheric scatter 212 occurring between the water
15 surface and the collection system. The fourth component is the upwelling light components 208 and 210 from the water column and the water plus object column, respectively.

20 As shown in FIG.2, for a given color channel X, the light collected by the sensor for pixels imaging the water column only is the result of upwelling radiance from the water column 208, plus the atmospheric reflection component 212, plus the sky reflection 216 and the
25 backscattered glint 220, or

$$(1) \quad U_{ix} = U_w + U_a + U_s + G'$$

where

30 U_w = upwelling radiance from the water column 208

U_o = upwelling radiance from the water column above the object **210**

G' = residual surface reflection from glint or whitecap **220**

5 U_a = atmospheric component **212**

U_s = Surface and hemispherical sky reflection component **216**

The light collected by pixels imaging the water column
10 with an object **204** is the result of the upwelling radiance from the object column **210**, plus the atmospheric component **212**, plus the sky reflection **216** and backscattered glint **220**, or

15 (2) $U_{2x} = U_o + U_a + U_s + G'$

The apparent contrast of an object for a single color water penetrating channel is then defined as

20 (3) $C_{ox} = \frac{U_{2x} - U_{1x}}{U_{wx}} = \frac{U_{ox} - U_{wx}}{U_{wx}}$

There are no atmospheric or surface reflection components present in the apparent contrast model. This does not imply that a dim object is detectable in the sensor
25 output containing a large background level. Temporal averaging (on the order of seconds) of multiple frames of data for a single color system can be used to reduce surface reflection clutter for fixed location objects from a fixed platform, but does not reduce the upwelling clutter component. As shown in **FIG.5**, the sensor line

output being integrated has a high background level intensity and the image has a large range between the brightest **502** and the dimmest portions **500** of the image with a dim object **504** embedded in the background. Typical 5 digital values of the brightest and dimmest values for a line output are 9600 and 5500 respectively in a 14-bit system (16384 counts), while the object may have a typical deviation from the line value of a few hundred digital counts. Removing the background to improve the 10 visibility and hence detection of surface or underwater objects may be performed by the following technique.

A second color channel Y can be chosen that is relatively water non-penetrating such that the object contrast is 15 weak or absent. The apparent contrast of the object for this channel is

$$(4) \quad C_{oy} = \frac{U_{oy} - U_{wy}}{U_{wy}}$$

20 As seen in **FIG.6A**, a typical line output for channel X **600** has a large background level that contains object **604**. The line output for a second channel Y **602** also has a large background level but contains a weak or absent object. The line outputs from the two channels (**600** and 25 **602**) are highly correlated except for the object. This implies that subtraction of the two line outputs can be used to enhance the detection of the low contrast object. Since the two line outputs have different average values, a weighting factor must first be calculated that 30 normalizes the line difference **606**. The average value of line X (**600**) and line Y (**602**) is determined. The

weighting factor **W** (322) is then computed as the ratio of the two line or frame averages, or

$$(5) \quad W = \bar{X} / \bar{Y}$$

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The values of line output Y are then multiplied by this weighting factor and subtracted from the line output from channel X to form a line difference 330.

10 (6) Line Difference = $X - Y(\bar{X} / \bar{Y})$

As seen in **FIG.6B**, by taking the weighted difference 606 between the highly correlated imagery in the two channels, one obtains low contrast object detection 608 15 based on the inherent contrast between the water and the object in the difference of the two channels. This process significantly amplifies the object contrast 608 against the residual background clutter. The detection process is greatly enhanced by the background reduction 20 and the typical weak signal amplification by a factor of 30 or more.

The signal level in the difference channel is

25 (7) $SIGNAL = K(C_{oy} - C_{ox})U_w$

where K is a proportional constant. The strength of the object detection signal available in the difference channel is directly proportional to the difference 30 between the apparent contrasts of the object in the two channels.

- The two channel multispectral process is shown in **FIG.3**. The digitized outputs of the multispectral sensor **218** are first captured **302** and stored in the memory of a frame
5 grabber card. Two of the three available colors, X and Y, are selected for the processing that follows. The fixed pattern noise of the sensor is measured in the three channels by placing the lens cap on the camera, taking multiple frames of data, and storing the average
10 resultant fixed pattern noise for the channels in memory. During subsequent image capture, the images subtract the fixed pattern **304** and **306** from the respective color before further processing.
- 15 Sensors exhibit a roughly linear response to the light input; i.e., the output signal doubles for a doubling of the intensity of light on the sensor. Deviation from this behavior is a non-linear response, which is measured for each pixel. A set of curve fitting coefficients is
20 calculated for each pixel or class of pixels. These coefficients are then used to calculate the correction to be applied to each pixel during frame readout, and are stored in a ROM **310** and **312** table lookup.
- 25 The average values of each line or frame **316** and **318** are computed for each color. A ratio **322** of the average values for the two selected colors is computed to determine the weighting factor to be multiplied **326** by one of the color outputs. This weighted output is then
30 subtracted from the other channel by a line subtractor **330** to produce the difference channel line output.

- Frames are built up from the difference channel line output. A local demeaning or whitening filter **332** is then applied to the resultant images on a frame-by-frame basis. This process acts to further flatten the image by
- 5 removing the local mean and tends to Gaussianize the image. This process increases the Probability of Detection (PD) and lowers the False Alarm Rate of the detection process. Additional processing on the resultant imagery **334** currently used in the industry such as frame
- 10 averaging where the frames have been corrected for motion during the stack and add process can now be implemented, and the resultant processed imagery can be displayed or transmitted **336** to a remote site for viewing.
- 15 In a preferred embodiment of this invention (FIG.7), the camera comprises a sensor **700**, a random access memory (RAM) **702**, a read only memory (ROM) **704**, and a multiple central processing units (CPU) **706**. The processed images can then be displayed on a monitor or LCD screen for
- 20 viewing **708**, as well as archived on a data storage unit **710** for later retrieval.

The parallel multispectral output from the sensor **700** is captured and fixed pattern corrected in unit **302**, **702**

25 which can be RAM, an application specific integrated circuit (ASIC), or a field programmable logic unit (FPGA). The multiple signals are linearized through a look up table stored in unit **312**, **704**, which may be ROM, an ASIC, or a FPGA. These signals are then processed **706**

30 by multiple CPUs, multiple digital signal processors (DSP), multiple FPGA's, or multiple ASIC's.

The algorithms, operating system, and system control files are stored in an operational file folder **712** that is downloaded to the appropriate units upon power turn on of the system. The algorithms and system control functions are then executed by the appropriate CPU, DSP, FPGA, or ASIC.